LEARNING OBJECTIVES

1. Recognize the primary radiation standards bodies and their roles in establishing radiation protection requirements.

2. Identify how radiation protection standards are implemented at TJNAF.

3. Identify responsibilities of management, workers, the RCG, and ARMs in TJNAF's radiation protection program.

4. Differentiate between the units used for exposure, dose, and dose equivalent.

5. State the basic quantity of radioactivity. Convert units of activity.

6. Describe how radiation energy is deposited in material.

7. State the quality factors for alpha, beta, and gamma radiations and the range of Q for neutron radiation.

8. State the dose limits for the whole body, extremities, and lens of the eye.

9. Discuss emergency dose guidelines.

STANDARDS, REGULATIONS AND LIMITS

For purposes of our discussion, the following definitions apply:

Standard - A practice recommended by an authoritative body, or a widely accepted “norm”.

Order - Unique to DOE contractors, Orders are pseudo-regulatory requirements which are implemented to the extent agreed upon in the contract.

Regulation - A specific set of instructions and requirements which must be demonstrably met by the regulated entity. Regulations are published in the Federal Register as part of the Code of Federal Regulations (CFR). The limits and other requirements in regulations are usually based on published standards.

Limit - The maximum (or minimum) value allowed by a regulation for some measurable quantity - usually associated with personnel dose, releases to the environment, or radiation levels.

Bodies involved in development of Radiation Protection Standards and Regulations

International Standards

ICRP - International Council on Radiation Protection

ICRU - International Council on Radiation Units and Measurement

IAEA - International Atomic Energy Agency

HPS - Health Physics Society

U.S. National Standards

NCRP - National Council on Radiation Protection

ANSI - American National Standards Institute

HPS

International Regulatory Agencies

IAEA

U.S. Regulatory Agencies

NRC - Nuclear Regulatory Commission

EPA - Environmental Protection Agency

DOE - Department of Energy

State Regulatory Agencies

DEQ - Department of Environmental Quality

BRH - Bureau of Radiological Health

Local Authorities

HRSD – Hampton Roads Sanitation District

ICRP Occupational Exposure Recommendations

- All exposures = As Low As Reasonably Achievable (ALARA)
- Effective dose equivalent = 5 rem/year
- Dose equivalent to lens of the eye = 15 rem/year
- Dose equivalent to individual organs (except lens of the eye) = 50 rem/year
- Planned special exposures = 2 x respective annual limit per event
= 5 x respective annual limit per lifetime
- Pregnant workers: limit work to conditions where it is unlikely that annual exposure will exceed 30% of annual limits.

NCRP Occupational Exposure Recommendations

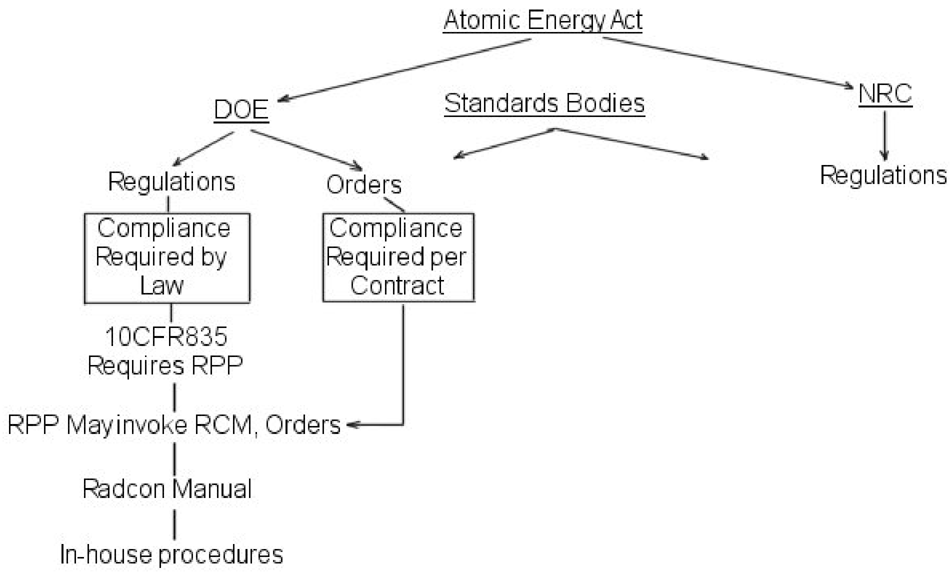
- All exposures = ALARA
- Effective dose equivalent = 5 rem/year
- Lifetime effective dose equivalent ≤ age in years x 10
- Dose equivalent to the lens of the eye = 15 rem/year
- Dose equivalent to individual organs (except lens of the eye) = 50 rem/year
- Dose equivalent to embryo-fetus = 0.5 rem; 0.05 rem/month
- Planned special exposures = 10 rem effective dose equivalent/event; 1 event/lifetime.

EPA Occupational Exposure Guidance

- All exposures = ALARA
- Effective dose equivalent = 5 rem/year
- Dose equivalent to the lens of the eye = 15 rem/year
- Dose equivalent to individual organs (except lens of the eye) = 50 rem/year
- Dose equivalent to occupational workers under 18 years of age = 1/10 applicable limit for adults
- Dose equivalent to unborn child of declared pregnant worker = 0.5 rem/entire gestation period.

IMPLEMENTATION OF REGULATIONS ORDERS AND STANDARDS

It is useful to look at the implementation of the various requirements as a hierarchy. This helps put in perspective the priority for compliance. We'll just look at the DOE related requirements.



When the Atomic Energy Commission (AEC) was restructured into the DOE and NRC, each new entity was given authority to enact regulations appropriate to protect workers and the environment. The NRC promulgated its radiation protection requirements early on in 10CFR20. January 1, 1996, the DOE enacted 10 CFR 835 - "Occupational Radiation Protection" - which, like 10 CFR 20 carries the force and effect of Federal Law. This regulation must be met and followed by all DOE contractor sites.

THE RPP - Incorporation by reference
10CFR835 requires each facility to produce and operate in accordance with a documented "Radiation Protection Program". The RPP is approved by DOE. At Jefferson Lab, the RPP is a list of all the stated requirements in the CFR, along with a brief description of how we meet each requirement. If the RPP states that we meet a requirement through some provision of the RadCon Manual, then that provision essentially becomes enforceable through reference as if it were part of the CFR. This same logic holds true for Orders or portions of orders which we commit to through the RPP.

RADIATION DOSE LIMITS

The goal of any program of radiation safety is to reduce exposure, whether internal or external, to a minimum. The external exposure reduction and control measures available should be of significant interest to all ARMs, in that the ARM may often be the first person encountering a new or unusual radiological situation. Keeping ALARA in mind should guide you toward action that helps prevent personnel exposures from which no benefit is obtained.

FEDERAL EXPOSURE LIMITS

United States Department of Energy radiation protection standards and program requirements for exposure of personnel to ionizing radiation.

Annual dose equivalent exposure standards for occupationally exposed workers:

- **Whole body - 5 rem (0.05 sievert)**
- **Lens of eye - 15 rem (0.15 sievert)**
- **Any other organ - 50 rem (0.5 sievert).**

Dose equivalent for an unborn child - Entire gestation period 0.5 rem (0.005 sievert).

Minors - An individual under the age of 18 shall neither be employed in, nor allowed to enter, controlled areas in such a manner that he or she exceeds 0.1 rem (0.001 sievert) per year (includes exposure to students under 18).

Public entering a controlled area:

- Effective dose equivalent received during direct onsite access shall not exceed 0.1 rem (0.001 sievert) per year.

- Exposures shall not cause a dose equivalent to any tissue (organ) to exceed 5 rem (0.05 sievert) per year.

Planned Special Exposures (PSEs)

For planned special exposures (non-emergency) in highly unusual situations where alternatives are not available, the total dose received in any year from PSEs (together with any other non-routine exposure) may not exceed 5 rem.

- Planned exposures must be approved in writing by the applicable DOE program office and the Assistant Secretary for Environment, Safety and Health (EH-1).

Emergency exposure during rescue and recovery activities:

- Actions should only be performed by volunteers.
- Each emergency worker shall be trained, and advised of the known or estimated risk prior to participation.
- No rigid upper dose limit for rescue and recovery, but individuals shall not be required to perform activities that involve “substantial personal risk”.
- The recovery of deceased victims shall be controlled within existing exposure limits, including the Planned Special Exposure provision.

DOE guidance on emergency dose is found in the Radiological Control Manual.

DOSE LIMIT	ACTIVITY PERFORMED	CONDITIONS
5 rems	All	Routine
10 rems	Protecting major property	Only on a voluntary basis where lower dose limit not practicable
25 rems	Lifesaving or protection of large populations	Only on a voluntary basis where lower dose limit not practicable
>25 rems	Lifesaving or protection of large populations	Only on a voluntary basis to personnel fully aware of the risks involved

FACILITY ADMINISTRATIVE EXPOSURE GUIDELINES

The DOE dose limits and TJNAF administrative control levels are summarized in the table:

Dose Limit Summary - Annual Limits

Category	DOE Dose Limit	TJNAF Action Level
Occupational - Whole Body	5 rem	1 rem
Occupational - Lens of the Eye	15 rem	3 rem
Occupational - Skin and Other Organs	50 rem	10 rem
Occupational - Extremities	50 rem	10 rem
Occupational - Declared Pregnant	0.5 rem (duration)	*
Member of the Public	100 mrem	10 mrem

*The TJNAF RadCon Manual states that once a pregnant female radiological worker has notified her supervisor, or medical services in writing of her pregnancy, TJNAF management ..."shall provide the option of a mutually agreeable assignment of work tasks, with no loss of pay or promotional opportunity, such that further occupational radiation exposure is unlikely." This policy is in effect a "TJNAF action level" which serves the same purpose as the other action levels listed. Should the declared pregnant worker desire to continue work in a manner which may cause exposure, more frequent dosimeter processing (monthly) would be established and an administrative guideline approximately equal to the minimum sensitivity of the dosimeter would be used.

Note: Limits are based on the sum of internal and external exposure.

ARMs Duties and Relationship to the RCG

ARMs Duties

Conduct and document routine radiation surveys and conduct non-routine surveys as requested by the RCG.

Investigate the causes of Radiation Alarms.

Correctly post Radiologically Controlled Areas and Radiation Areas on the basis of measurement.

Promptly notify the RCG upon discovery of any un-posted High Radiation Area during a survey; securing the area to prevent access.

Relocate CARM probes as requested by RCG.

Continuously monitor workplace activity for adherence to TJNAF RadCon Manual requirements.

Monitor, tag, and control potentially radioactive components.

ARMs Relationship to RCG

During the conduct of ARM duties, ARMs work for and are responsible to the Radiation Control Group. When performing surveys or other radiation protection related work, the ARM's NUMBER ONE PRIORITY must be radiation safety. In effect, an ARM is a member of the RCG. To that extent, any abnormalities or difficulties encountered during the conduct of ARM duties should be reported to the RCG (and the Crew Chief). This includes anomalies noted during surveys, etc. and lack of support from line management in the conduct of duties. TJNAF senior management is holding laboratory staff, line management, and supervisors responsible for quality EH&S activity. Both acceptable and unacceptable conduct as an ARM may be reflected on job performance evaluations.

Tasks ARMs May Not Perform

ARMs Will Not:

- Free release any potentially radioactive component.
- Be a part of a work crew for any activity they monitor.
- Approve the release of water, other liquids or gases from potentially activated systems.
- Relocate RBMs, CARMs, or CARM probes, reset CARM trip levels, take failed CARMs or RBMs out of service, or modify CARMs or RBMs in any way without approval and specific instructions from the RCG staff.
- Evaluate sample analysis results, dosimetry results, or RBM data to determine compliance with state or federal requirements.
- Approve movement of radioactive material outside Radiologically Controlled Areas.
- Be responsible for posting, designating, or *controlling access to High or Very High Radiation Areas, Contamination Areas, or Airborne Radioactivity Areas.

* This means providing ‘coverage’ or managing work/entry into the area. ARMs may act as a “guard” to temporarily prevent access to HRAs pending RCG arrival, if he/she has notified the RCG, can do so from outside the HRA and in a fashion consistent with ALARA.

Quantities and Units

RADIOACTIVITY

The Curie (Ci). Originally, the Curie applied only to radium, being taken as the number of disintegrations per unit time occurring in one gram of pure radium. This unit was eventually standardized to any type of radioactive material and is defined numerically as 37 billion disintegrations per second, or 3.7×10^{10} dps. Equivalently, 1 Ci = 2.22×10^{12} dpm. Subunits are usually used for the quantities of radionuclides found in the workplace (i.e. milli-, micro-, etc.).

The SI unit for activity is the **Becquerel** (Bq). 1 Bq = 1 dps.

For workplace measurement of surface contamination, the dpm is often used to quantify radioactivity. Since instruments used to detect surface contamination usually read out in counts per minute (cpm), a simple conversion to dpm can be made by dividing the observed count rate by the counting efficiency of the instrument (cpm/dpm). The activity stated in dpm can then be converted into curies or becquerels if desired.

Standard field contamination surveys are performed using filter wipes by "swiping" an area approximately 100 cm^2 in area and using a "frisker" type instrument to obtain a count rate. Alternately, a direct frisk of the surface can be used where background radiation levels are low.

EXAMPLE

A surface "swipe" of an item is counted on a frisker. The instrument has a background count rate of about 50 cpm. The total count rate of the sample + bkg is 200 cpm. What is the removable surface activity in dpm? In Ci, Bq? Frisker efficiency is assumed to be approximately 10%.

EXPOSURE AND DOSE

The term "exposure" when used loosely means the condition of being exposed. However, when used as a unit, the term has a specific definition. Exposure is quantified in units of charge liberation per volume or mass of air.

Roentgen (R): The quantity of X or gamma radiation that will produce ions carrying one electrostatic unit (esu) of charge in 1 cubic centimeter of dry air under standard conditions. In the SI system, exposure is measured in units of C/kg and there is no special unit.

$$1 \text{ R} = 1 \text{ esu/cc}$$
$$1 \text{ R} = 2.58 \text{ E}^{-4} \text{ C/kg}$$

Exposure is a measure of the ions produced, or ionizing ability of photons. Exposure is a useful quantity because it can be directly measured (as charge or current flow). Exposure is limited in concept by several factors:

- it refers to photons only
- air is the only defined medium
- it is not defined at photon energies over 3 MeV

Absorbed Dose (D)

The absorbed dose is a measure of the energy imparted to matter by ionizing radiation per unit mass of the irradiated material.

RAD (radiation absorbed dose): 1 rad = 100 ergs/gram

SI unit: Gray (Gy): 1 Gy = 1J/kg = 100 rad

Some features that distinguish absorbed dose:

- the quantities for absorbed dose refer to all types of ionizing radiation
- the specification of D in any medium is appropriate
- the absorbed dose is a measure of the energy imparted, not charge produced

Dose Equivalent (H)

Laboratory and epidemiological observations have led to the conclusion that different types, and/or energies of ionizing radiation can have differing biological effects in humans. To account for and normalize these differences, the quantity *Dose Equivalent* is used. Since dose equivalent is a measure of overall biological harm done, it is useful to think of it as a unit of relative risk for radiation exposure. Dose equivalent is not a physically measurable quantity - it is a *derived* quantity.

REM (Roentgen Equivalent Man): The rem is historically defined as the amount of any type of ionizing radiation that would have the same biological effect as exposure to 1R of X or gamma radiation. Numerically, the rem is equal to the dose in rads times the quality factor (Q); H = DQN, where H is in rem, D is in rad, and N is other modifying factors that may be appropriate.

The SI unit for dose equivalent is the sievert (Sv) and is related to the rem by 1 Sv = 1 J/kg = 100 rem. Although the sievert is given a physical quantity, this quantity is only valid when Q=1. The sievert is defined by H=DQN, where H is in Sieverts, and D is in gray.

The salient features of dose equivalent include:

- the dose equivalent is not a physical quantity, so it can not be measured directly - it is derived from the measurement of one of the physical quantities (eg. RAD)
- the concept and quantities are useful for radiation protection work (i.e. risk management), not radiation physics
- the definition implies that the dose equivalent may vary depending on conditions of exposure, such as when the area of the body irradiated is not uniform (in this case, the concept of *effective dose equivalent* comes into play).

QUALITY FACTOR (Q)

The quality factor is used to relate absorbed dose from various types of radiation to the biological damage caused to the exposed tissue. The numerical value of Q is based partly on the results of laboratory radiobiological experiments and partly on data from epidemiological studies. The final value of Q is *assigned* to a particular radiation based on the available radiological data and other information related to the ionizing capability of the radiation.

Points to remember about Q:

- Q is for use in radiation protection work in deriving the relative risk from a given absorbed dose
- Q is not an experimentally determined quantity, it is an <u>assigned</u> value
- Q does not apply to acute exposures above about 10 rad

Latest Values for Radiation Weighting Factors (Quality Factor) from ICRP 60

Type and energy range	Radiation Weighting Factor (w_R = Q)
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil, > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

It should be noted that an exposure of 1R in air causes an absorbed dose (in air) of about 0.87 rad. Moreover, that same exposure would cause an absorbed dose (on average) of ≈ 0.98 rad to soft tissue. In addition, the Q for photon radiation is unity. Therefore, for field measurements of roughly uniform, low dose rate <u>photon</u> radiation, it is acceptable to simply equate all three of the basic exposure/dose units.

For photon radiation:

$$1\ \text{R} \approx 1\ \text{rad} \approx 1\ \text{rem}$$

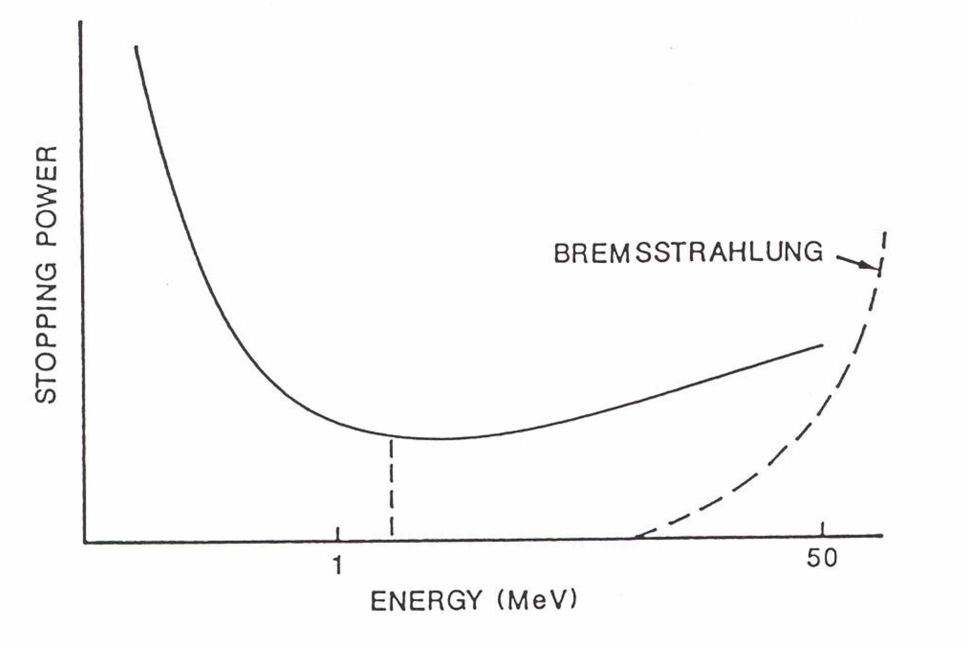
TYPES OF RADIATION AND THEIR INTERACTIONS

Alpha - has +2 charge and mass of 4 amu. Interacts by direct ionization/excitation. The highly charged alpha particle loses energy through coulombic interactions in matter. Because of the high charge, will interact with a high *specific ionization*, causing it to loose all its energy in a very short path length. Maximum range in air is several centimeters. Maximum range in tissue is less than 100 microns. Alphas are easily shielded by air, paper, clothing, or the dead layer of outer skin on the body (about 70 microns thick).

Beta - A high energy electron (but by definition originates in the nucleus during radioactive decay) . May be positively charged (positron). Interacts through direct ionization/excitation through charge interactions in matter, but the specific ionization is much lower than for alpha particles. Hence, the range is greater. Relatively easy to shield typical beta particles of moderate (< several MeV) energy. Good shields are low density materials such as lucite and aluminum. Range of beta particles in air is about 3 m/MeV. Energetic betas may penetrate tissue to the depth of the lens of the eye (3mm) or further in some cases. Primary concern is dose to the skin. (Beta particles >~ 2 MeV can reach the “deep dose” depth)

Beta radiation (electrons) also interacts by the bremsstrahlung process. Bremsstrahlung is the emission of a photon (X-ray) by an electron (beta particle) when the electron encounters the dense electrical field in the vicinity of a nucleus as it traverses matter. This interaction “deflects” the path of the electron, drastically changing its momentum. In order to conserve momentum, a photon containing the balance of energy lost by the electron is emitted.

Bremsstrahlung production varies directly with both the Z of the material and the energy of the electron. For beta particles of 1MeV, only about 3% of the energy is converted to bremsstrahlung in lead. In the case of high energy electrons, however, very intense bremsstrahlung fields are created by the interaction of the electrons with matter. For medium Z materials, this radiative energy loss mechanism dominates the interactions above 50 MeV.

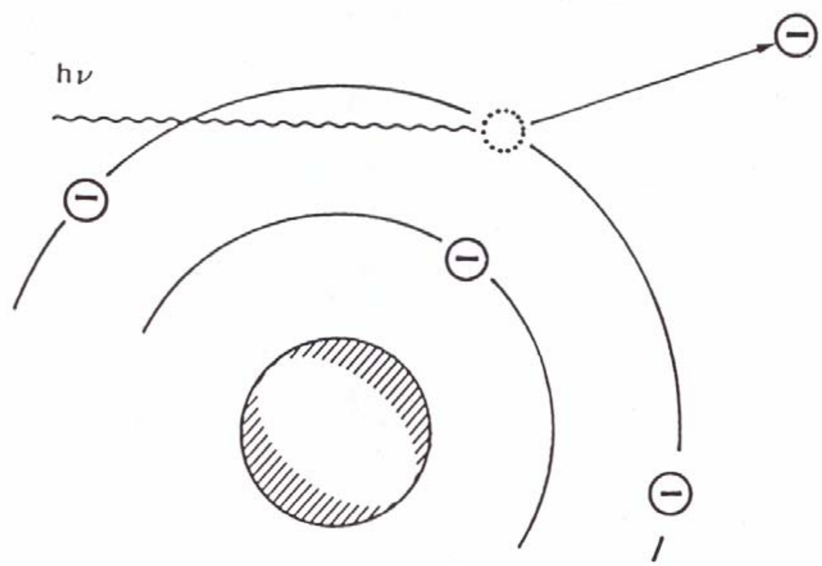


General shape of the beta stopping power curve

Photons - gamma /x-ray radiation is electromagnetic energy having no mass or charge and propagating at the speed of light. Relatively low specific ionization, which gives rise to great range. The best shields are dense materials such as lead which have a large electron density. Probability of interaction is directly proportional to the electron density in the absorber. Gammas easily penetrate tissue, giving rise to the concept of "whole body" irradiation (results in Deep Dose). The three main types of interactions with matter are Photoelectric Absorption, Compton Scattering and Pair Production. At high energies (above ~ 10 Mev in most materials), photonuclear interactions begin to occur.

Photoelectric Effect

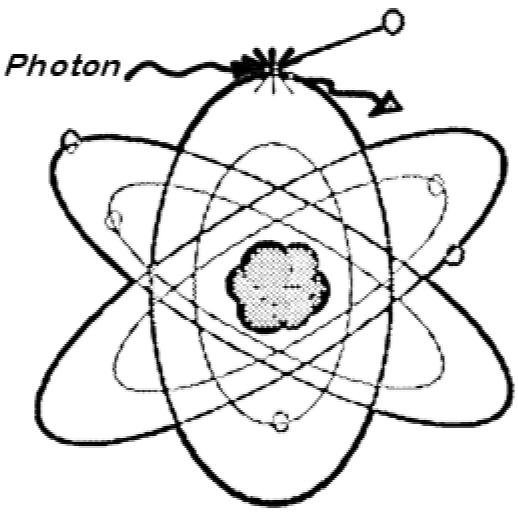
In the photoelectric effect, the photon transfers all of its energy to an orbital electron. In the process, the original photon disappears, and its energy is transferred to the electron as kinetic energy. The electron is elevated to a higher energy level and is ejected from its orbit, carrying the full photon energy (minus the binding energy). The resulting *photoelectron* can then go on to ionize other atoms. Photoelectric effect is important for photon energies < 1 MeV.



1. Photon strikes electron imparting all energy to electron and consequently disappearing.
2. As a result, the electron is freed from orbit and travels on with kinetic energy

Compton Scattering

In Compton scattering, the photon can be thought of as scattering off of an electron, giving up a portion of its energy to it and continuing on with a lower energy. The electron moves away with the remaining portion of kinetic energy. More accurately, it is an absorption-re-emission process where the re-emitted photon and electron share the initial photon's energy. Compton scattering is important for photon energies between 200 keV and 5 MeV and predominates in most photon interactions in common materials.

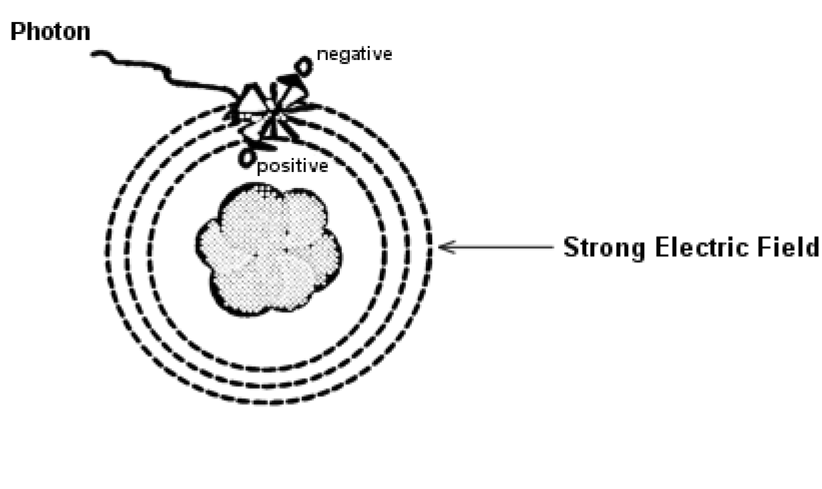


Photon continues on in different direction with less energy

Electron is freed from orbit, becomes "Compton electron"

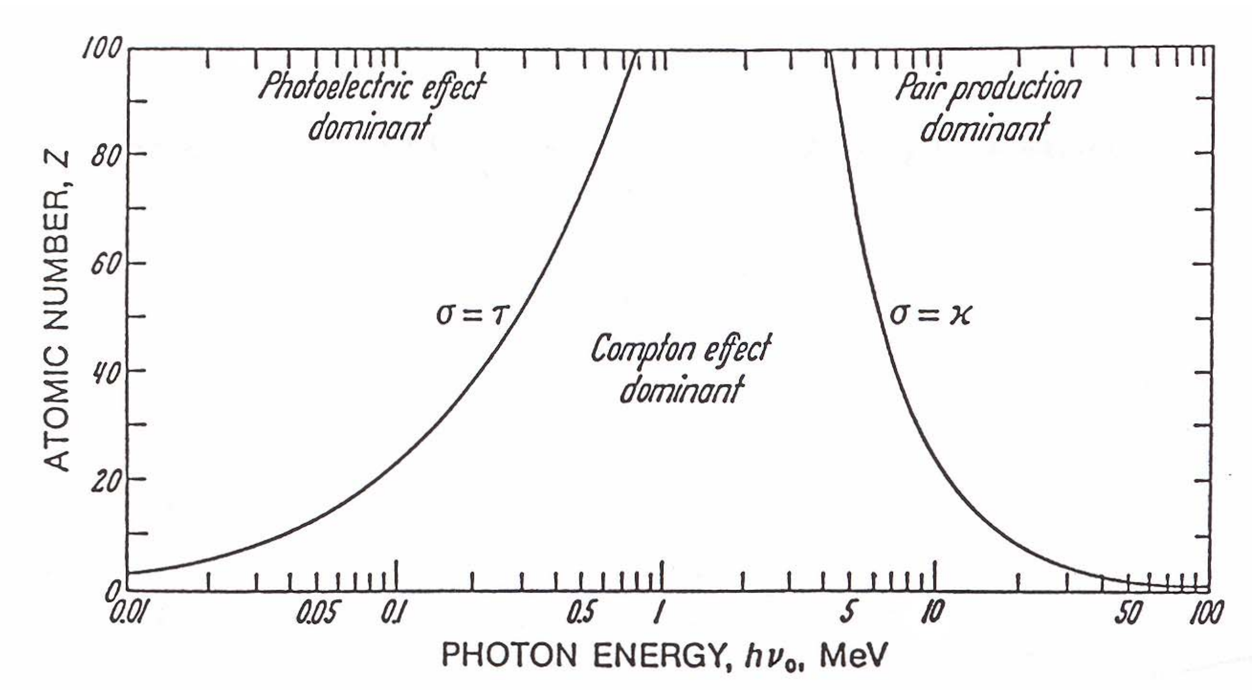
Pair Production

In pair production, a photon of sufficient energy gives up all its energy near the nucleus of an atom to form a *positron-electron pair*. Since the rest mass of an electron is .511 MeV, the formation of the pair requires a theoretical minimum photon energy of 1.02 MeV. However, the process does not become important until about 5 MeV, where it begins to dominate gamma interactions. In the process, the initial photon is eliminated, giving up its energy in excess of the threshold energy to the pair as kinetic energy (with a small amount given to the nucleus to conserve momentum).



Photonuclear Interactions

When photon energy is above about 10 MeV, *photonuclear* interactions (such as γ-n) become an important interaction mechanism. The primary importance of these interactions at TJNAF is that they result in (1) a significant neutron flux being generated where beam interacts with matter, and (2) the production of *activation products* or radionuclides as a result of the nuclear disruption caused in the target nuclei.



Neutrons - described in terms of broad energy range values such as *thermal*, *intermediate*, and *fast*. Neutrons are ejected from excited nuclei following nuclear interactions which may be initiated by a variety of events such as (α,n), (γ,n), (d,n), etc. Neutrons do not interact directly with orbital electrons and hence are not directly ionizing. However, they undergo a variety of interactions which cause secondary ionizing events to occur. The interactions are generally classified under the broad classifications of Radiative Capture, Elastic Scattering, and Inelastic Scattering.

Neutron capture is dominant in the thermal energy range and also occurs in some intermediate interactions. The result of the capture of the neutron is an excited nucleus which then emits a gamma ray or charged particle. This secondary particle/photon causes the ionization in the material. For dose to tissue, the (n,γ) reaction in ^{1}H is an important contributor to dose. During the absorption process, a 2.23 MeV gamma ray is emitted. The nucleus is changed to ^{2}H in the process. The absorption process is responsible for most *neutron* activation.

Elastic Scattering is a type of interaction in which kinetic energy is conserved. These interactions can be thought of as "billiard ball" collisions. Elastic scattering is important in fast and intermediate energy neutron interactions. The energy transfer in elastic collisions is greatest when the target nucleus has a mass close to that of the neutron (eg. hydrogen). When energy loss is high, the result is greater attenuation of the neutron field. This is why hydrogenous materials such as water and polyethylene are used commonly as neutron shielding. By following up with a neutron absorbing material, an effective shield would first slow and then capture the neutrons.

Inelastic Scattering occurs in neutron interactions beginning with intermediate and going on to very high energy. In inelastic scattering, the scattering event itself does not appear to conserve momentum. Several types of inelastic events may take place - in most events the neutron is pictured as momentarily being absorbed by the nucleus, then re-emitted with a lower energy. The nucleus is left in an excited state and then returns to ground state by emission of a photon. For very high energy neutrons, inelastic scattering and other nuclear interactions (eg. spallation) become dominant.

Neutron Energy Categories

Thermal	~ < 0.5 eV*
Intermediate	~ 0.5 eV - 10 keV
Fast	~ 10 keV - 10 MeV
Relativistic	~ > 10 MeV

*Nominal energy for thermal neutron is 0.025 eV

References for Unit 1

1. *Radiological Safety Aspects of the Operation of Electron Linear Accelerators*, Swanson, IAEA Publication 188, 1979.

2. *Operational Health Physics Trainiing*, Moe, ANL-88-26, 1988.

3. *The Health Physics and Radiological Health Handbook*, Shleien, 1992.

4. TJNAF Radiological Control Manual, May 24, 1999

5. DOE Standardized Training for Radiological Control Technologists

6. 10CFR835, Occupational Radiation Protection

LEARNING OBJECTIVES

1. Describe prompt radiation production from electron beams.

2. Describe the characteristics of activation products at electron accelerators.

3. Characterize the relative amounts of exposure from various source terms at TJNAF.

4. Describe the stochastic risk model and its inference regarding chronic exposure.

5. Differentiate deterministic risks from stochastic risks.

6. State the ALARA concept and its implementing tools.

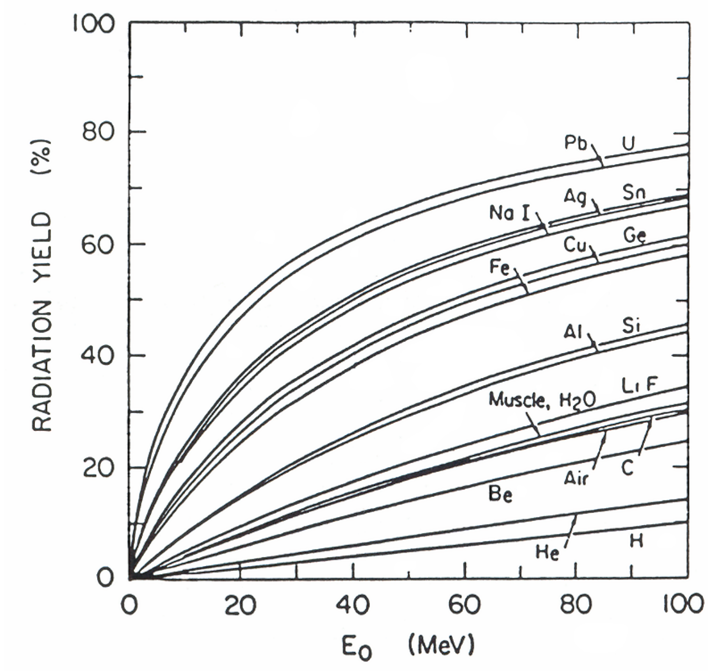
7. Describe ancillary sources of radiation at TJNAF.

SOURCE TERMS AT TJNAF

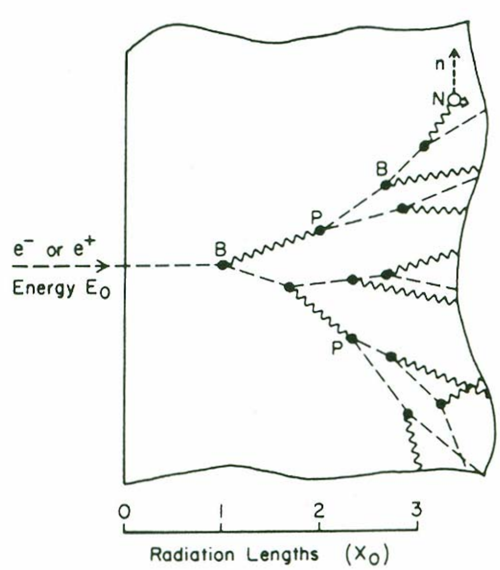
The phrase *source term* is used to describe the combination of various factors and conditions - from radiation production to physical locations, shielding, etc. - which result in personnel radiation exposure.

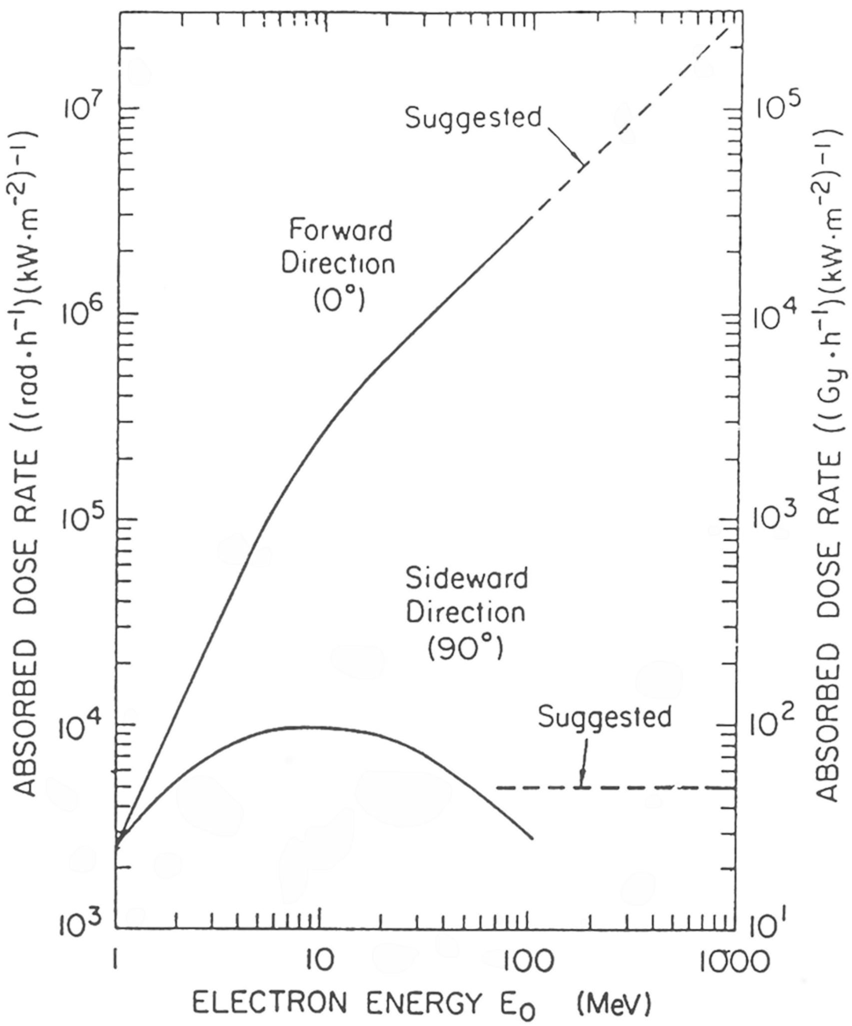
Accelerator sources can be split into two broad categories. These are direct or *prompt* radiation, and activation or *residual* activity.

<u>Prompt Radiation</u>
The dominant prompt radiation from electron beams of any energy is photon radiation. The initiating events are bremsstrahlung interactions which cause a broad spectrum of x-rays to be produced up to nearly the initial electron energy. An electron may undergo multiple bremsstrahlung interactions. At higher energy, when the photons produced exceed the pair production threshold, a secondary source of high energy electrons (the electron-positron pair) and photons (the annihilation radiation) is generated. In turn, these electrons and photons contribute to further electron-photon production through the bremsstrahlung/pair-production process.



This cascade of photons and particles is often referred to as "electron-gamma shower" or "electromagnetic cascade". This shower propagates to some maximum depth (dependant on the material), where energy loss ceases to be dominated by radiative mechanisms, at which point the shower falls off. The external photon radiation emitted from some target will at first increase with the target thickness, reach a broad maximum, then decline approximately exponentially. A target of the thickness which causes the maximum radiation is known as "optimum" target. The radiation produced by such a target and all related references are described by the term "thick target".





Thick target bremsstrahlung

Rule of Thumb, where E_o> 20 MeV :
For 0° bremsstrahlung - Dose rate at one meter (rad/min/kW) ≈ 500 E_o
For 90° bremsstrahlung - Dose rate at one meter (rad/min/kW) ≈ 83

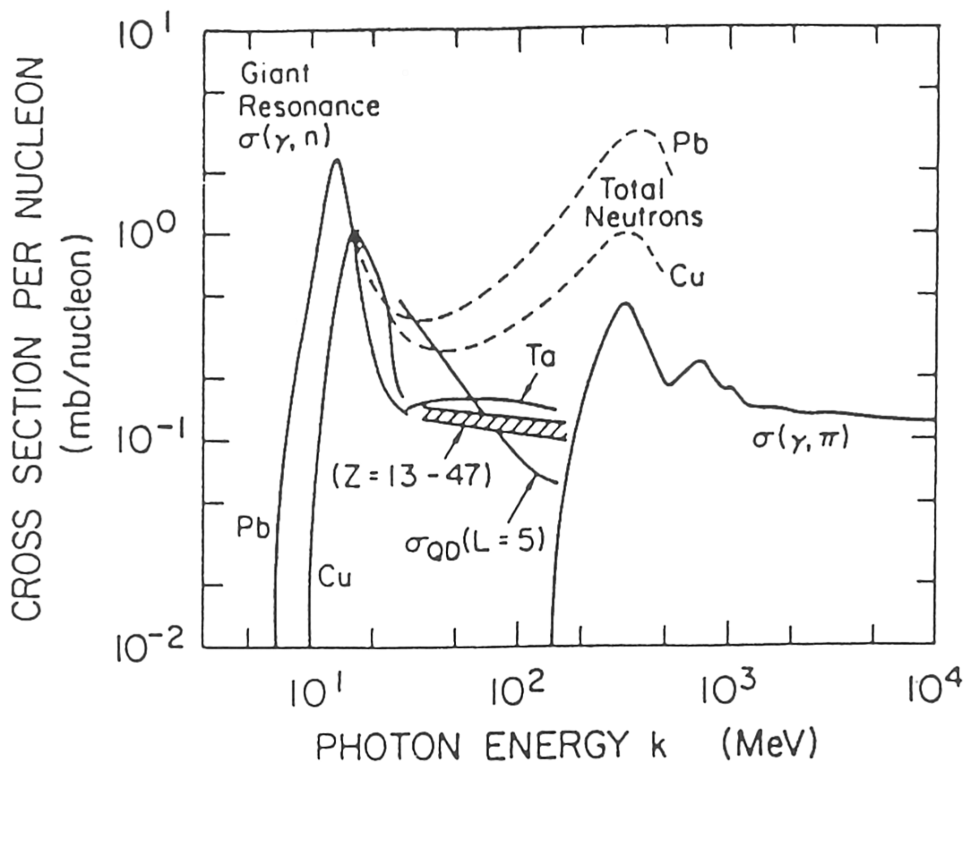
Neutrons represent the second major source of prompt radiation at electron accelerators. Above a threshold energy (generally, about 10 MeV), neutron radiation will be produced by any material struck by the electron or photon beam. In effect, the "gamma shower" which occurs at lower energy is modified to become a "neutron/gamma shower" at energies above the neutron production threshold. It is of note that the neutron production from the *photons* is many orders of magnitude greater than from the electron beam itself for thick targets. In very thin targets, electroproduction of neutrons may dominate. It is the release (and to a lesser degree, the subsequent capture) of neutrons which produces the radionuclides found in accelerator components.

There are three main neutron production mechanisms. They are characterized by energy ranges in which each dominates.

The Giant Photonuclear Resonance - Between threshold energy and about 35 MeV, giant resonance neutrons predominate. The process can be pictured as the transfer of energy from the electric field of the photon to the nucleus by the induction of an oscillation in which the protons as a group move oppositely to the neutrons as a group. One or more neutrons may be ejected as a result of the oscillation.

The Quasi-Deuteron Effect - Above the giant resonance peak (30-40 MeV), the quasi-deuteron effect begins to dominate neutron production. This effect is thought of as an interaction between the photon and a neutron-proton pair within the nucleus; hence the name 'quasi-deuteron'. The production cross section for QD is about an order of magnitude below the giant resonance. This combination serves to add a high energy 'tail' to the giant resonance neutrons.

Photo-pion Production - Above 140 MeV, pi mesons become a source of high energy neutrons. Although the cross section for producing these neutrons is much smaller than that for the giant resonance, the neutrons produced are much more penetrating, and (for high energy machines) make the largest contribution to neutron dose rates outside the shielded enclosure.



Residual Radioactivity

In addition to direct radiation, many of the interactions just described give rise to induced radioactivity in accelerator components. The process is often referred to as "activation".

The activated materials can be broadly classified as *photo-activation* products and *neutron activation* products.

Photo-activation is caused mainly by:

- Loss of neutrons from giant resonance and quasi-deuteron interactions (γ,n), (γ, np), etc.

- High energy photo-spallation (γ, sp)

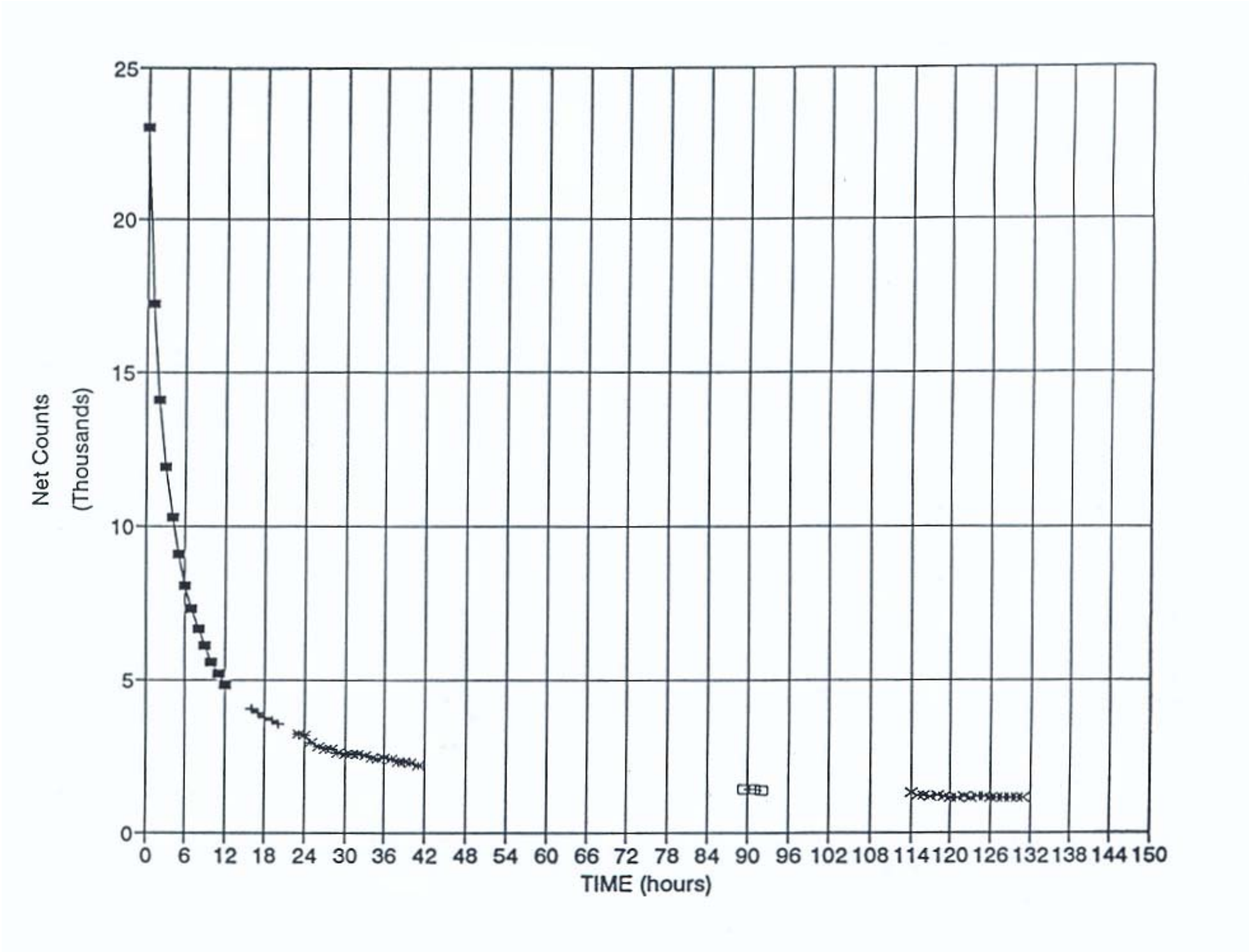
Components located close to the beam path are the most susceptible to photoactivation. The highest energy photons are produced in a forward directed beam. Objects in close proximity to the beamline are most susceptible to this beam. Components typically subject to photo-activation include:

- Dumps
- Targets
- Collimators
- Magnets
- Any narrow beam aperture (eg. extraction septa)
- Any point of beam scraping or loss
- Dump cooling water

Photoactivated materials tend to:

- be neutron deficient
- have "short" half-lives (months)
- build up relatively quickly (as a function of their half-life)
- decay by positron or electron capture modes
    - positrons always result in photon (annihilation) radiation
    - electron capture decay has no charged particle emission (gamma only)

The graph on the following page shows the decay for a sample of activated material removed from the CEBAF beamline. Most of the components in the material had half-lives on the order of days to months and are well represented by the chart on page 25.



Neutron activation can occur from high energy neutron spallation or by the capture of neutrons which have been moderated to low energies.

Since this activation occurs in materials subjected to a nearly isotropic neutron flux rather than a directional high energy photon beam, items subject to neutron activation are not as restricted to near-beamline items as in the case of photoactivation products. Any material in a beam enclosure, including the structure itself may be subject to neutron activation. The specific activity of this material tends to be much lower than for photon activation products.

In contrast to photoactivation, neutron activated materials tend to:

- be neutron rich
- have long half-lives (months to years)
- build up relatively slowly
- decay by beta emission
    - beta emitters often emit gamma radiation also

It is important to remember that activation can occur in any material subjected to the accelerator's activating primary radiation field. Materials other than the more obvious beam line components which may become activated include lubricants, cooling water, and air that is contained in spaces within the beam enclosure. Electronic components may be activated as well as damaged by the radiation flux. Lead used to shield dumps or experimental setups may become activated. Closed cooling systems associated with beam dumps are subject to a build up of activation products that can present a radiation and contamination hazard during maintenance activities on these systems.

The main source of personnel radiation exposure at Jefferson Lab during normal operation will be exposure to activation products during maintenance in the beam enclosure or on activated cooling water systems.

TABLE XXVIIIb. RADIONUCLIDES DETECTED IN STEEL SHIELDING (special units)

Nuclide	Half-life	Specific activity (t = 0)[a] ($\mu Ci \cdot g^{-1}$)	Γ[b] Specific gamma-ray constant ($(R \cdot h^{-1})(Ci \cdot m^{-2})^{-1}$)	Specific exposure rate[c] ($(\mu R \cdot h^{-1})(g \cdot m^{-2})^{-1}$)
Mn-56	2.576 h	130.	0.86	111
Cr-51	27.8 d	16.	0.76	12
Mn-52	5.60 d	7.5	2.18	16
Mn-54	303 d	5.2	1.20	6.1
V-48	16 d	3.1	1.95	6.0
Fe-59	45.6 d	1.6	0.62	1.0
Sc-44m	2.44 d	1.0	1.47[d]	1.5[d]
Sc-46	83.9 d	0.35	1.09	0.37
K-43	22.4 h	0.21	0.57	0.12
Cr-48	23 h	0.19	0.97	0.18
Sc-48	1.83 d	0.17	1.78	0.30
Co-58	71.3 d	0.11	1.13	0.12
Co-60	5.263 a	0.060	1.30	0.077
Co-57	270 d	0.050	1.29	0.064

[a] At time of accelerator turnoff, t = 0.
[b] See Footnote 14 (Section 2.6).
[c] Exposure rate at 1 m, per g of activated steel, at time of accelerator turnoff. Uncorrected for self-shielding and distribution of activity.
[d] Includes Sc-44 daughter radiations.

TABLE XXXIIb. PHOTOACTIVATION PRODUCTS FROM O-16 IN WATER (special units)

Nuclide	$T_{\frac{1}{2}}$		MPC_w [a] ($\mu Ci \cdot cm^{-3}$)	Γ [b] Specific gamma-ray constant $((R \cdot h^{-1})(Ci \cdot m^{-2})^{-1})$	Reaction type	Threshold (MeV)	Cross-section [c] σ_{-2} ($\mu b \cdot MeV^{-1}$)	A_s [c,d] Saturation activity ($Ci \cdot kW^{-1}$)
O-15	123	s		0.59 (β^+)	(γ,n)	15.67	75	9
O-14	70.91	s	–	1.60 (β^+)	(γ,2n)	28.89	(1)	(0.1)
N-13	9.96	min	–	0.59 (β^+)	(γ,2np)	25.02	0.9	0.1
C-11	20.34	min	–	0.59 (β^+)	(γ,3n2p)	25.88	3	0.4
C-10	19.48	s	–	1.01 (β^+)	(γ,4n2p)	38.10	(1)	(0.1)
Be-7	53.6	d	0.02	0.029 –	(γ,5n4p)	31.86	0.3	0.04
H-3	12.262	a	0.03	– (β^-)	(γ,H-3)	25.02	1.5	0.2

[a] ICRP recommendation for the general public, 168-hour week occupancy. See test for discussion.
[b] See Footnote 14 (Section 2.6).
[c] Values in parentheses are rough estimates.
[d] Saturation activity in water per unit electron beam power. Assume 100% direct absorption of electron beam power in water. Activity in water will be less in most situations where the beam absorber is water-cooled metal. Values shown are obtained directly from Approximation A and apply at high energies. For $E_0 \gtrsim 50$ MeV, the value for O-15 may be reduced by a factor of two, and others by an even larger factor.

Residual Contamination

Loose surface contamination can be caused by activation of:

- surface coatings - dust, paint, rust, or oxidation (even on stainless steel)
- sealants, grease, anti-seize compounds
- cooling water - photoactivation products cause high dose rates during operation, activation of impurities in the systems is long term contamination hazard
  - Highest concentrations found in filter and resin media
  - "crud traps" accumulate contamination over long-term
- air in the beam enclosure - the particulate activation products may build up on surfaces or be concentrated in air handling and filtering systems

Because of the nature of these materials, they may not be accessible until maintenance or disassembly of the components and systems. Therefore, maintenance on items where contamination potentially exists requires RadCon surveillance.

TABLE XXXb. ACTIVITY INDUCED IN AIR (special units)

Produced nuclide			Parent nuclide				Cross-section[b]	A_s[c]
Nuclide	$T_{\frac{1}{2}}$	MPC ($\mu Ci \cdot cm^{-3}$)	f Abundance[a]	Nuclide	Reaction type	Threshold (MeV)	$\Sigma f\sigma_{-2}$ ($\mu b \cdot MeV^{-1}$)	Saturation activity ($\mu Ci \cdot m^{-1} \cdot kW^{-1}$)
H-3	12.262 a	2×10^{-3} [d]	1.562 0.424	N-14 O-16	(γ,H-3)	22.73 25.02	(3)	(140)
Be-7[f]	53.6 d	1×10^{-6} [d]	1.562 0.424	N-14 O-16	(γ,sp)[f]	27.81 31.86	(0.6)	(30)[f]
C-11	20.34 min	3×10^{-6} [e]	1.5×10^{-4}	C-12	(γ,n)	18.72	0.011	0.5
			1.562 0.424	N-14 O-16	(γ,sp)[f]	22.73 25.88	(6)	(300)[f]
N-13	9.96 min	2×10^{-6} [e]	1.562	N-14	(γ,n)	10.55	310	14000
O-15	123 s	2×10^{-6} [e]	0.424	O-16	(γ,n)	15.67	32	1500
N-16	7.14 s	5×10^{-7} [e]	4.0×10^{-4}	O-18	(γ,np)	21.81	(0.01)	(0.5)
Cl-38	37.29 min	2×10^{-6} [d]	4.6×10^{-3}	Ar-40	(γ,np)	20.59	0.13	6
Cl-39	55.5 min	3×10^{-6} [d]	4.6×10^{-3}	Ar-40	(γ,p)	12.52	0.86	40
Ar-41[g]	1.83 h	2×10^{-6} [e]	4.6×10^{-3}	Ar-40	(n,γ)	–	–	–[g]

[a] Fraction of air by volume, multiplied by atoms/molecule.
[b] Abundance f times integral cross-section σ_{-2}. (See Eq.(8) of Section 2.2). Values in parentheses are rough estimates.
[c] Per bremsstrahlung pathlength in air (metres) and electron beam power (kW) incident on a thick high-Z target. Values in parentheses are rough estimates.
[d] Based on ICRP recommendation for radiation workers, 40-hour week, exposure from inhalation.
[e] Based on ICRP recommendation for radiation workers, 40-hour week, semi-infinite cloud (see text).
[f] Spallation reaction.
[g] Neutron-capture reaction. Occurs where high neutron fluences are moderated by water or concrete shielding.

Volume activated material normally does not present a loose contamination hazard except during activities such as:

- machining
- grinding
- burning/welding

Generally, where contact dose rates do not exceed a few millirem per hour, contamination from these activities is unlikely, **however ARMs are not authorized to allow these activities on any activated material.**

Where contamination is not likely, surveys may be limited to radiation dose rate surveys only. The activated materials are controlled based on external radiation levels.

Other Sources of Radiation

A few other sources and types of radiation bear mentioning. Along with the types of prompt radiations already mentioned, mu mesons may be part of the beam-generated flux emanating from targets and stops. Muons are charged particles similar to electrons but about 200 times more massive. Muons become a significant portion of the primary radiation beam only at energies above 1 GeV. This muon beam is very collimated in the forward direction. Some muons may be produced outside the end station shielding from the decay of pions. Muons interact only by ionization/excitation (they are too heavy to undergo bremsstrahlung), and consequently have very long path lengths.

Non-Accelerator Sources

The most common non-accelerator sources are small isotopic sources or x-ray generators used in experimental detector setups and for instrument calibrations and checks. These sources are controlled by a source custodian. Custodians are responsible for:

- ensuring only authorized personnel use their sources
- ensuring the sources are used in accordance with applicable restrictions
- maintaining a source use log, keeping the log up to date
- notifying the RCG in case of loss, damage, or abuse of a source

Radiation Generating Devices which can produce measurable external radiation fields must be used under auspices of the RCG as delineated in a Radiation Control Operating Procedure or other safety procedure which addresses radiation safety requirements such as an OSP which has been reviewed by the RCG.

- EEL building
  - Source lab
  - Portable x-ray tube
  - Cabinet x-ray machine

- Test lab
  - Vertical Test Area
  - Cryo-test cave
  - Injector test cave

Klystrons produce x-rays (from bremsstrahlung) when operating, however the klystrons used in the CEBAF accelerator are self shielded by design and operate at relatively low voltage. Klystrons used in the FEL require external shielding and may require area postings. Test Lab RF operations may also employ klystrons requiring local shielding and other controls. **Any maintenance which disturbs the installed shielding or experimental work with these devices, or new designs and design changes should be brought to the attention of the RCG for evaluation.**

In general – any device combining high voltage (>10 kV) and a vacuum is a potential x-ray hazard, and should have a hazard analysis done prior to use.

Dose and Risk - ALARA

A review of some definitions.

Somatic - Any effect which occurs in an exposed person.

Heritable (genetic) - Any effect which occurs in the offspring of exposed individuals (but does not include teratogenic effects). Such effects arise from changes in chromosomes in the sperm/ovary.

Teratogenic (pre-natal) - An effect which is caused by exposure received *in-utero.*

Acute - A relatively large dose of radiation (for whole body dose, generally > 10 rad) in a short period (hours to days).

Chronic - A long term or protracted exposure to radiation where the dose is relatively evenly distributed or is received in small increments.

Stochastic - A dose-response relationship (risk model) in which the *probability of occurrence* of some effect is seen to increase with dose.

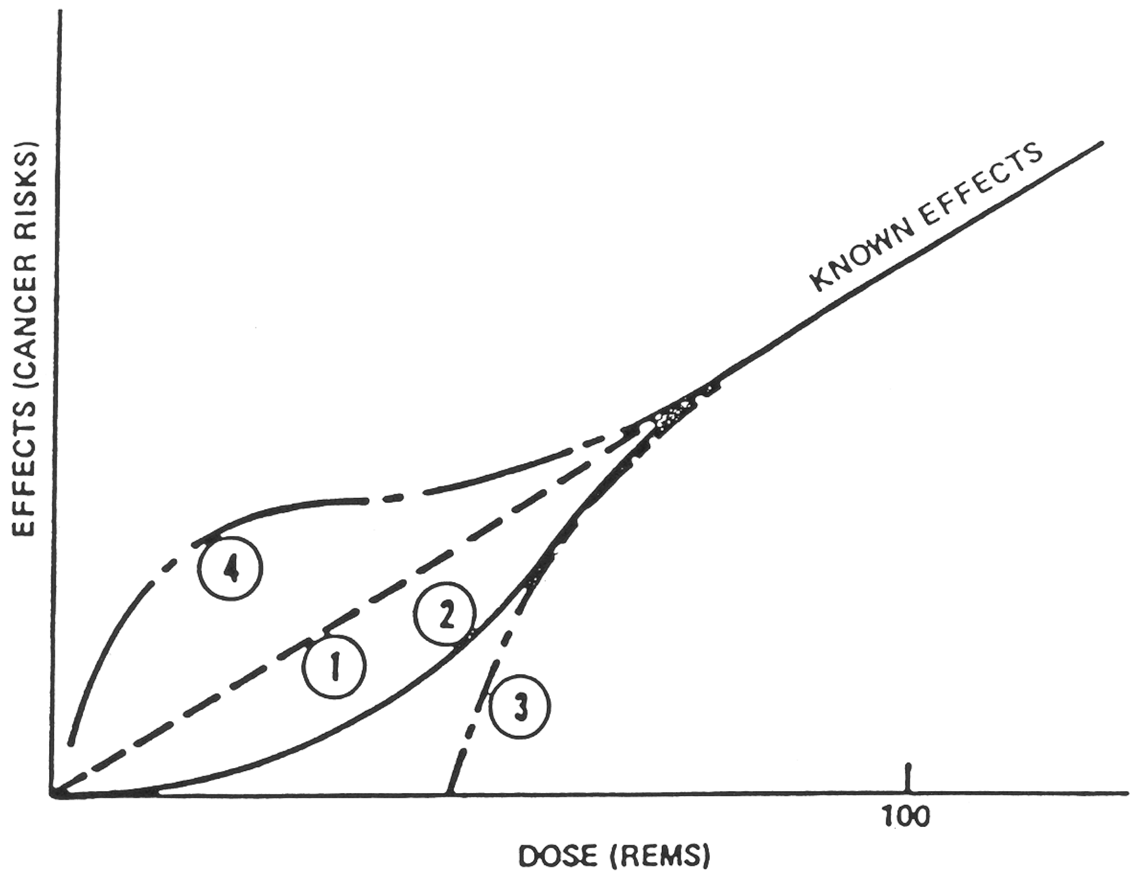
Deterministic - A dose-response relationship in which the *severity of the effect* increases with dose.

The relationship between risk and exposure mode (acute or chronic) can be placed in a simplified matrix.

	Risk for Deterministic Effects?	Risk for Stochastic Effects?
Can acute dose cause -	Yes - Thresholds appear at various levels for different effects. Classified as "early" somatic effects.	Yes - Probability of occurrence varies in ≈ linear manner with dose. Classified as "latent" effects.
Can chronic dose cause -	Some - A few deterministic effects can occur with long term exposure IF dose exceeds the threshold for the effect.	Yes – but occurrence is not measurable at occupational doses. Probability for occurrence is extrapolation from high doses.

	Therapeutic Range – 1 to 10 Sv				Lethal Range – Over 10 Sv	
Range:	Subclinical 0 to 1 Sv	1 to 2 Sv	2 to 6 Sv	6 to 10 Sv	10 to 50 Sv	Over 50 Sv
Incidence of Vomiting:	None	1 Sv: 5% 2 Sv: 50%	3 Sv: 100%	100%	100%	100%
Delay Time:	-	3 Hours	2 Hours	1 Hour	30 min	30min
Leading Organ:	None	Hematopoietic Tissue			G.I.Tract	Central Nervous System
Characteristic Signs:	None	Moderate Leukopenia	Severe Leukopenia, Hemorrhage, Infection, Purpura, Epilation Above 3 Sv		Diarrhea, Fever, Disturbance of Electrolyte Balance	Convulsions, Tremor, Ataxia, Lethargy
Critical Period Post-Exposure:	-	-	4-6 Weeks		5 to 14 Days	1 to 48 Hours
Therapy:	Reassurance	Reassurance, Hematologic Surveillance	Blood Transfusions, Antibiotics	Consider Bone-Marrow Transplantation	Maintenance of Electrolytic Balance	Sedatives
Prognosis:	Excellent	Excellent	Good Therapy Effective	Guarded Therapy Promising	Hopeless Therapy Palliative	
Convalescent Period:	-	Several Weeks	1 to 12 Months	Long	-	
Incidence of Death:	-	None	0 to 80% (Variable)	80 to 100% (Variable)	90 to 100%	
Death Occurs Within:	-	-	2 Months		2 Weeks	2 Days
Cause of Death:	-	-	Hemorrhage, Infection		Circulatory Failure	Respiratory Failure Brain Edema

Summary of Clinical Effects of Acute Ionizing Radiation Doses.[9]



Points to remember about Latent Risk estimates:

- Damage is known to occur, but is repaired, preventing prompt observable effects.
- Risk for latent injury appears stochastic
- No threshold for risk known, but background occurrence rates, low probability and individual differences in response make finding threshold impossible. Therefore:
    - Risk is assumed to be non-threshold
    - Probability simplified to linear model (but is linear-quadratic)
    - Risk for cancer ~ 4 per 10,000 person rem (based on occurrence at high dose)
    - Risk for genetic effects significantly lower - not demonstrated measurably in any exposed human populations

ALARA

The ALARA concept grows out of our assumption that any radiation exposure carries with it some risk. ALARA itself is the effort to maintain both individual and collective dose As Low As is Reasonably Achievable, taking into account the net benefit obtained as a result of the exposure. A fundamental principle underlying the ALARA concept and radiation control at TJNAF is that *"There should not be any occupational exposure of workers to ionizing radiation without the expectation of an overall benefit from the activity causing the exposure."*

Implementing ALARA at TJNAF

The Radiological Control Group is responsible for:

- Implementing radiological requirements, limits, guidelines, and procedures.
- Monitoring radiological work in progress to ensure radiologically safe practices are used.
- Measuring, documenting, and tracking personnel exposures and environmental impact of radiological work.
- Evaluating radiological performance and advising TJNAF management in implementing improvements.

AS AN EXTENSION OF THE RCG, THE ARM MUST ACCEPT AND CARRY OUT ALARA RESPONSIBILITIES BEYOND THAT EXPECTED FROM OTHER RADIATION WORKERS.

The ARM is often the first person to encounter radiological conditions which might have changed or which exceed criteria for additional radiological controls. You are expected to:

- Recognize conditions which require controls beyond those present
- Anticipate the effect of planned activities within a radiological area
- Keep ALARA first when performing radiation-related tasks
- Advise others on the radiological conditions
- Stop or prevent work or access to areas which requires additional controls
- Notify the RCG when conditions require it or when ALARA is not being observed

Hazard Mitigation (ALARA)

Radiological controls are all implemented for the goal of dose reduction. As with any hazard identification/mitigation system, the ALARA principle is applied through a combination of engineered and administrative controls.

Engineered Controls

Engineered controls are the preferred method of implementing ALARA. Engineered controls consist of equipment designed to protect personnel from a hazard by preventing access to enclosures, providing a warning of the hazard or a means to remove the hazard. These controls may be active or passive. Examples of engineered controls include:

Shielding

Ventilation

Interlocks

Containment

Administrative Controls

Engineered controls alone may not completely remove a hazard. Administrative controls are often used in minimizing dose during work where there is a relatively low radiation risk. Examples of administrative controls are:

Configuration Control (used in conjunction with engineered controls)

Training

Posting

Work control documents

PPE

Remember the basic ALARA elements of Time, Distance, and Shielding. These simple ideas can be used to implement safe work practices in the most complex radiological situations.

A few basic practices related to time, distance, and shielding are listed below. Sometimes obvious ALARA techniques are overlooked - take the time to think about them.

Time - Delay entry or activity in the area if practical. Don't use radiological area as short cut.

Distance - Don't sight-see. Use meter to stay in ALARA area and HELP OTHERS DO THE SAME.

Shielding - Get RCG help and advice. Never move without contacting RCG. Keep in mind things such as earth shielding or water. Leaking water shields may look OK but become ineffective.

- -

References for Unit 2

1. *Radiological Safety Aspects of the Operation of Electron Linear Accelerators*, Swanson, IAEA Publication 188, 1979.

2. *Operational Health Physics Trainiing*, Moe, ANL-88-26, 1988.

3. *The Health Physics and Radiological Health Handbook*, Shleien, 1992.

4. TJNAF Radiological Control Manual, May 24, 1999

5. DOE Standardized Accelerator Training

6. *Risks Concerning Occupational Radiation Exposure*, Nuclear Regulatory Commission, Regulatory Guide 8.29. RADIATION DOSE LIMITS